Quaternary Science Reviews 146 (2016) 134–146

Contents lists available at ScienceDirect

Quaternary Science Reviews

journal homepage: www.elsevier.com/locate/quascirev

A persistent Holocene wetting trend in arid central Asia, with wettest conditions in the late Holocene, revealed by multi-proxy analyses of loess-paleosol sequences in Xinjiang, China

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ARTICLE INFO

Article history:
Received 9 June 2015
Received in revised form
1 June 2016
Accepted 4 June 2016
Available online 28 June 2016

Keywords:
Holocene
Loess-paleosol sequence
Moisture trend
Wettest late Holocene

ABSTRACT

There are significant differences in the interpretation of the moisture (precipitation) history of arid central Asia (ACA) during the Holocene, as inferred on one hand from speleothem oxygen isotope records, and on the other from lake sediments. Here we present the results of measurements of climatically-sensitive magnetic properties and soil color from four well-dated loess-paleosol sequences from the northern slopes of the Tienshan Mountains and the Yili River valley, Xinjiang, China, in the core area of ACA. Our results demonstrate that the characteristic Holocene paleosol, indicating relatively moist conditions, generally formed after ~6 ka (1 ka = 1000 cal yr BP) in the study region, and that the accumulation of unweathered loess prevailed during the early Holocene, indicating a dry climate at that time. The magnetic proxies further reveal a trend of generally increasing moisture since the Last Glacial Maximum, with the wettest climate occurring during the late Holocene. This trend of increasing moisture during the Holocene is representative of the Xinjiang region and possibly of the whole of the core area of ACA, and is in marked contrast both to the mid-Holocene moisture maximum observed in the East Asian summer monsoon region and to the general decrease in the strength of the Indian summer monsoon since the early Holocene. Our findings are supported by the results of a climate simulation which indicate a trend of increasing summer and winter precipitation during the Holocene in the core area of ACA, caused mainly by an increase in the strength of the westerlies effected by an increasing latitudinal insolation gradient and by a negative trend of the Arctic Oscillation (AO) or North Atlantic Oscillation (NAO).

1. Introduction

Arid central Asia (referred to as ACA in this paper), including the central Asian countries, NW China and the southern Mongolian Plateau, is located in the central and eastern part of the middle latitude Eurasian continent and is the largest non-zonal arid region in the world (Fig. 1a, Chen et al., 2008). ACA is climatically controlled by the westerlies and is characterized by scarce water resources, sparse vegetation cover and fragile ecosystems, making it very sensitive to climate change. During historical times, large-amplitude moisture changes have resulted in the enlargement or shrinkage and even disappearance of lakes, the expansion or contraction and even desertification of oases, and these changes constitute the environmental background against which kingdoms rose and declined in these arid areas (Litvinsky et al., 1996; Soucek, 2000; Brooke, 2014). During the recent period of anthropogenic global warming, precipitation has increased in the arid Xinjiang area of China (Shi et al., 2007) and in the arid central Asian countries (Chen et al., 2011), resulting in previously desiccated lake basins filling with water and the renewal of lakes (Shi et al., 2007).

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http://dx.doi.org/10.1016/j.quascirev.2016.06.002
0277-3791/

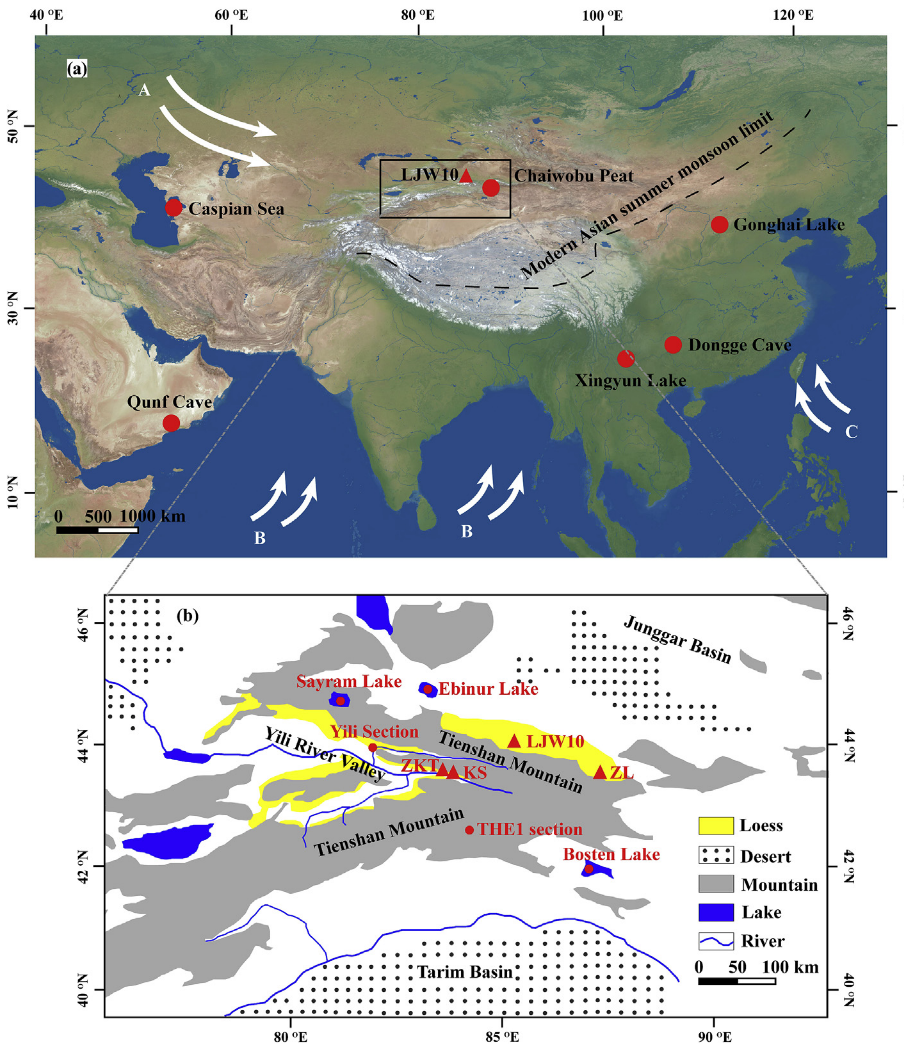

Fig. 1. (a) RS image of arid central Asia with the dashed line indicating the present Asian monsoon limit (after Chen et al., 2008, 2010). Also shown are the dominant atmospheric circulation systems (arrows with upper case letters) of the Westerlies (A), Indian summer monsoon (B), and East Asian summer monsoon (C). (b) The geomorphology and physical geography of our study area. The four studied loess-paleosol sections are indicated by red filled triangles in (a) and/or (b). Other Holocene records referenced in the text are indicated by filled circles. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

As one of the major source areas for global atmospheric dust (Prospero et al., 2002), ACA plays an important role in global biogeochemical cycles and climate system dynamics (Jickells et al., 2005; Mahowald et al., 2005; Uno et al., 2009). Furthermore, the variations in land surface processes, vegetation types and surface albedo in this arid region can directly influence the local and regional climate (Dirmeyer and Shukla, 1996). Consequently, increasing attention has been paid to improving our understanding of the processes and possible mechanisms of climatic and environmental changes in ACA on various time-scales (e.g. Ding et al., 2002a; Frechen and Dodonov, 1998; Chen et al., 2006, 2008, 2010; Holmes et al., 2009; Mischke et al., 2010; Huang et al., 2013; Leroy et al., 2013).

The present Holocene interglacial is a period of significant development of civilization, and therefore understanding its climatic evolution is important for the long-term prediction of changes in the human living environment. Our synthesis of evidence from lake sediments (Chen et al., 2008) indicates that the pattern of moisture evolution in ACA is characterized by a dry early Holocene, the occurrence of wettest conditions in the mid-Holocene, and a moderately wet late Holocene, and exhibits an "out-of-phase" relationship with the pattern of monsoonal evolution in eastern monsoonal Asia. The proposed "westerly-dominated regime" of ACA moisture changes, and the possible mechanism responsible, has attracted increasing research interest in recent years (e.g. Li and Morrill, 2010; Jin et al., 2012; Hong et al., 2014; Wang et al., 2013). Climate simulations indicated that the dry climate during the early Holocene in ACA can be mainly attributed to reduced water vapor advection caused by decreases in westerly wind intensity and in evaporation upstream (Jin et al., 2012). Results from lake energy- and water-balance models suggested that high lake levels in ACA during the mid-Holocene were caused by increased precipitation associated with the westerlies (Li and Morrill, 2010). This modelling work proposed a possible mechanical explanation for the "westerly-dominated regime" of moisture changes in ACA during the Holocene. Recent studies of an aeolian sand-paleosol sequences (Long et al., 2014) and of lacustrine sediments (An et al., 2012; Wang et al., 2013) support the occurrence of generally dry conditions during the early Holocene in the Xinjiang region (Huang et al., 2009). However, this is in contrast to conclusions based on a pollen *Artemisia*/Chenopodiaceae (A/C) record (Li et al., 2011) and a speleothem oxygen isotope record (Cheng